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Cambridge, Mass.

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ADAPTIVE CHARACTERISTICS OF MANUAL TRACKING*

by

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I. INTRODUCTION

A considerable body of experimental and analytical work has been built up on the problem of description of the human operator in a simple tracking task, (1, 2, 3, 4,). Efforts to describe the closed-loop tracking characteristics of the operator have led to several types of quasi-linear continuous and sample data models. Each recognizes that the subject changes his tracking parameters in order to achieve satisfactory performance under the given conditions of controlled element dynamics and input characteristics. The adaptive nature of manual tracking is particularly intriguing, and we have focused our attention on the human operator's process of adaptation to sudden changes in the controlled element dynamics.

We have attempted to find the answers to two major questions in this investigation:

(1) What time is necessary for this adaptation process to take place?

(2) What is the process by which the human adapts to a new control mode, and what information does he use to adapt?

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This paper is a report on some of the preliminary findings that have been gathered from two series of experiments on manual tracking.

II. THE TRACKING SITUATION

The subject is seated in a small cubicle approximately 6-feet in height, 2-1/2-feet wide and 4-feet long. Placed on the wall directly in front of him is a 21-inch display oscilloscope positioned at eye level and approximately 36-inches from the subject. The visual indicators on the display are a 1/2-inch diameter circle and a small dot. For pursuit tracking the target signal, or input, is a horizontal displacement of the circle. The subject controls the small dot and is instructed to keep the dot within the circle so as to minimize the absolute error. For compensatory tracking the circle remains stationary in the center of the oscilloscope and the horizontal displacement of the small dot is proportional to the error, that is, the difference between the input and the subject's response. Once again the subject is instructed to keep the dot within the circle.

The subject makes his response by moving his control stick. The stick protrudes through a circular hole in the right-arm rest of a student's chair on which the subject is seated. The control stick is spring restrained and is easily manipulated by a wrist movement, requiring one pound for maximum deflection. The stick can be moved approximately plus and minus 45 degrees from its upright position. The right and left movements of the stick provide the voltages for the input to the control dynamics. The control system dynamics are simulated on an analog computer. A switching mechanism enables us to change modes only when the input to the control dynamics is zero. Thus a control transition to any one of eight different modes without introducing any position discontinuity in the response display can be made.

To observe the subject's adaptive ability, we allow him to track under a certain control mode and then switch the control mode without warning. The subject will observe an increase in his tracking error and change his manual tracking characteristics in accordance with the new control system modes. In our preliminary experiments we concentrated on control system dynamics which were simple gains, providing a straight position control for the subject. We allowed eight different control modes consisting of gains of 1, 2, 4, and 8 combined with either positive or negative polarities. With a unity gain full left and right deflection of the control stick produced a ± 6-inch deflection on the display oscilloscope.

III. AVERAGE TRANSITION ERRORS

Inspection of individual transient response records corresponding to changes in polarity or gain, or both, yielded very little consistency in the adaptations or error characteristics. Part of this difficulty may be ascribed to the input signal which contributed to the error, and part of it to variation in the individual subject's adaptation characteristics. To expose consistencies in the adaptation process, we computed the average error waveform following a given type of control transition using our PDP-1 digital computer for the computation. The examples of average error waveform shown below represent the computed averages of twenty transition error processes. These figures given rather good indications of both the times involved for adaptation and the mechanisms which the operator appears to be using to adapt. All of these average error records were taken with compensatory tracking.

Fig. 1 is the average transition error for a change in polarity of the control system. The input for this experiment was a single sinusoid at 0.1 cps. Notice that the average error rises sharply for the first 0.5 sec. and then decreases rapidly to its asymptotic level at about 1 sec. and following the change in control system polarity. Because the error decreases sharply after 0.5 sec. has passed, on the average the adaptation process must take place in less than 0.5 sec. after the polarity reversal. The adjustment time, the time necessary for the error to reach an asymptotic level is approximately 1 sec.

Fig. 2 shows actual time tracings on input, subject's response and error signals prior to and following a polarity reversal from gain +2 to -2, the type summarized in the average error curves of Fig. 1. The adaptation process illustrated in Fig. 2 is fairly typical of those used in the average of Fig. 1. The upper trace shows the input (which was a sinusoid for this case) and the response. Notice that after transition, because of the polarity reversal, the response began moving in the wrong direction. The error increased sharply after 0.3 sec. and then was reduced abruptly at 0.7 sec. as the subject reversed his own polarity and moved the control stick in the opposite direction. The second channel indicates what the response would have been if the system were in its pre-transition mode, i. e. a gain of +2. Note that for the first 0.3 sec. the response on channel 2 follows the input very closely clearly indicating that for this time the subject continued to track as though the polarity of the control were still positive.

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* Note that the average error has a major component at the input frequency which represents the steady state compensatory error in tracking the input sinusoid.

The third channel represents the difference between subject's response and the input. This is the error that was displayed on the oscilloscope in the compensatory tracking task and is also the error that was averaged in the average response computation. We see that it clearly indicates that the subject reversed the polarity of his response at 0.7 sec., the time at which the error begins to decrease.

The fourth channel is a recording of the absolute value of the error passed through a low-pass filter with time constant 0.25 sec. This channel is used to estimate adjustment time. In this case, the estimated adjustment time is about 1.0 sec., which happens to be the average adjustment time determined from the average error curve of Fig. 1.

The average error curve of Fig. 3 shows the results of a sudden control gain increase from +1 to +4. The initial effect of the gain increase is an immediate increase in error. As the subject seeks to eliminate this error, he causes the response to overshoot and quickly produces an error of opposite sign. Notice that on the average the first corrective movement took place after 0.2 sec. Of particular interest in this figure is the observation that the second peak is of no greater amplitude than the first one. An unadapted control loop would exhibit oscillations of increasing amplitude when its gain was multiplied by a factor of 4. Thus some adaptation must have taken place before 0.6 sec., the time of the second peak. Following this second peak, the average error then decreases monotonically and reaches the asymptotic level in another 0.6 sec., yielding an adjustment time for this type of transition that is approximately 1.2 sec.

The time records of Fig. 4 illustrate the adaptation process for one of the responses that corresponds closely to the average response shown in Fig. 3. The initial result of the gain increase is an overshoot in response lasting for 0.2 to 0.3 sec. The corrective movement made in an effort to reduce this error results in an overshoot to the opposite side which peaks at 0.6 sec. Notice that the amplitude of the overshoot to the opposite side is of the same magnitude as the original error that the subject was attempting to nullify. Since the total extent of the response was only twice that which was necessary to reduce the error, and not four times the error, we can see that the human operator achieves a significant amount of gain reduction by the time this second movement is completed. Following the second peak, the error is gradually reduced. Neglecting the small oscillations which continue for nearly four seconds, the adjustment time for this particular transition is approximately 1.1 sec.

The record of Fig. 5 is an average error response for a transition having both an increase in gain and a change in the polarity of the control. Adaptation to this transition required both a change in polarity and a decrease in gain. Notice that the average error response contains features seen in both Fig. 1 and Fig. 3. The time taken to reach the first peak, the point at which the subject reverses the polarity of his response, is 0.4 sec., approximately the same as the adaptation time to a simple polarity reversal, (Fig. 1). The overshoot reaching its peak at 0.8 sec. indicates that even after polarity had been corrected gain reduction is still required. Thus the necessity of adapting to two changes (polarity and gain) leads to a somewhat longer adaptation time and a longer adjustment time (approximately 1.5 sec.).

A typical transition record for this type of control change is shown in Fig. 6. For the first 0.5 sec. following the transition, the response diverges from the input. When a polarity reversal is finally made at 0.5 sec., the gain remains somewhat elevated leading to the overshoot with peak at 0.9 sec. , and final gain reduction only after about 1.0 sec. The adjustment time indicated on this particular record would be 1.4 sec.

The fourth type of transition considered here is a simple gain-decrease from a gain of +4 to a gain of +1. Such a transition produces a very small initial error when tracking a low-frequency signal and would cause no serious consequences in system performance if adaptation were not to take place. The average error following such a transition is shown in Fig. 7. Notice that the magnitude of the error remains quite small, and that the time of adaptation is not clearly defined. The total adjustment time for this type of transition lies in the region of 1.4 sec.

To be certain that the average error recordings shown above were not artifacts resulting from the simple sinusoidal input signal, we substituted an input signal consisting of a low-frequency rectangular spectrum band limited at 0.24 cps., and repeated the process of averaging errors following control transitions.

Fig. 8 is the average error following a polarity reversal (+2 to -2) taken with this random input. Notice that its shape is quite similar to the curve of Fig. 1, which was obtained with a sinusoidal input. The major difference is the lack of the slow sinusoidal component seen in Fig. 1, which was an artifact of the sinusoidal input signal. The presence of the area of negative error in Fig. 8 may or may not be a result of the characteristics of the random input signal. Fig. 9 shows the average error following transitions consisting of a gain increase from +1 to +4 using the same random input. Notice that this error curve is quite similar in form to that of Fig. 3 which was obtained using the sinusoidal input.

IV. FACTORS AFFECTING ADJUSTMENT TIME

In an effort to set bounds on the adjustment time following changes in control gain and polairty, as well as to determine those factors which contribute most heavily to determining the adjustment time, we ran a series of experiments on five trained subjects tracking under both pursuit and compensatory situations. Each subject was scored on 180 transitions in pursuit and compensatory tracking. For each transition we recorded the adjustment time, which was taken to be the time required for the filtered absolute error to decrease to three times its median asymptotic level and remain below this criterion for three seconds.

This type of measure appears to have an extremely large variance and makes it quite difficult to say much about the factors affecting adjustment time with any degree of confidence. There were, however, several effects which did emerge above the noise level. Primary among these was the importance of the type of display on determining the adjustment time. The median adjustment time for compensatory tracking over all types of transitions averaged (over subjects) 3.5 sec. For pursuit tracking it was 2.5 sec. when using a pursuit display.*

In a pursuit display the separate presentation of input and response enables the subject readily to detect changes in his response characteristics and therefore to go about the necessary

*For these tests the input spectrum was a band limited rectangular spectrum of cutoff frequency 0.64 cps. This more difficult spectrum presumably accounts for the longer adjustment times than those shown in the average transition error curve of part III above.

adaptation process. In the compensatory situation, however, the separation of his response from the input by means of the displayed error signal is far more difficult, and therefore the process of identifying the control system dynamics and adjusting one's response accordingly is slowed considerably.

In the course of these experiments we examined the effect of the number of allowable transitions. In the most general case, a transition could take place between any two of the eight possible control modes, whereas in the most limited situation the transitions consisted of merely switching back and forth between two particular pre-selected and practical control modes.The measured adjustment times did not show any strong dependence on the number of modes under which the transitions were taken, although this possible effect is still under investigation. It appears that certain characteristics of the error provide the subject with a great deal of information as to the possible mode to which he may be switching, and therefore effectively partition the very large number of possible transitions into a much smaller set of transitions associated with obvious error characteristics. Thus, for example, all of the simple polarity reversals are relatively easy to identify because the error moves in exactly the opposite direction of that expected by the subject. We find that adjustment times for such polarity reversals tend to be smaller than for many other types of transactions, and also to show low variance.

V. DISCUSSION

In the results presented we are dealing solely with position control systems, thus only two questions need to be answered by the operator:

1. What is the direction in which I must move the stick?
2. What is the magnitude through which I must move the stick?

We have examined a very simple hypothesis in which the answers to these two questions are the basis of the adaptation process. In the compensatory tracking situation, the information on which these gain and polarity decisions are based are the observed error and (possibly) some proprioceptive information on wrist positions.

If, on the last movement, the error kept its same sign and increased then a polarity reversal should be suspected. Similarly, if on the last movement the error increased but changed its sign, then a gain increase should be expected. And finally, if on the last movement the error decreased, but less than the amount desired, (that is, did not go all the way to zero) then a gain decrease should be expected. Naturally, each of these observations is hampered by the presence of disturbance in the form of the input to the system, since in the compensatory situation the error represents the effect of the input as well as that of the response. An adaptive control model for the human operator based on changing gain and polarity in accordance with the answers to the above questions, enables one to correctly predict the approximate form of the average error curves shown in this paper.

Although a simple model of this sort may be appropriate for the position control situation, it may require considerable modification when dealing with more complex tracking tasks. We are presently increasing the number of control modes and considering the effects of more complicated control dynamics.

There is nothing in the present data which denies the possibility of a mode switching type of human behavior.

VI. CONCLUSIONS

The ensemble average technique applied to the error signal following changes in control system characteristics appears to give a relatively clear picture of the process of adaptation. It also identifies the approximate times required for the human operator to adapt to a control change and to complete his adjustment to this change. The average error curves of part III indicate that for the very simple situation under investigation, the adaptation times are on the order of 0.5 to 1.0 sec. Once having adapted, or taken on the correct strategy to go with the new control system mode, the subject requires only an additional 0.3 sec. or so to complete his adjustment to the new control mode. This is merely one basic movement time or sampling period if one considers a sampled data model for the human operator. It must be emphasized that the results shown in part III are preliminary results only, taken on one subject with a simple position control in the compensatory mode. The ensemble average technique does, however, appear to be a useful tool for investigating the adaptation process which otherwise defies both sophisticated and simple-minded analysis techniques.

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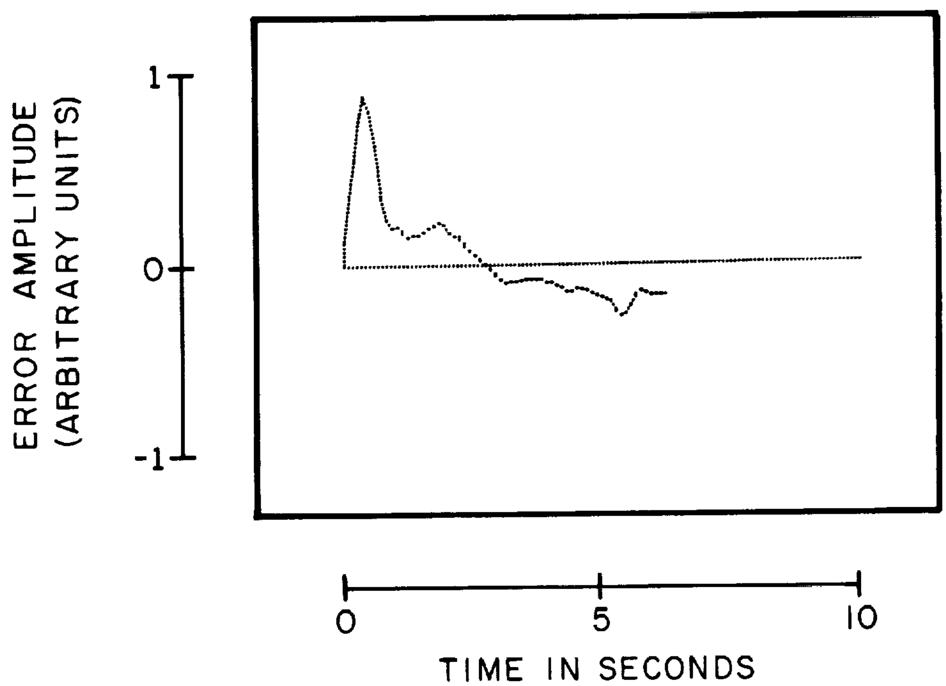

FIG. 1 AVERAGE ERROR FOLLOWING POLARITY REVERSAL (+2:-2)

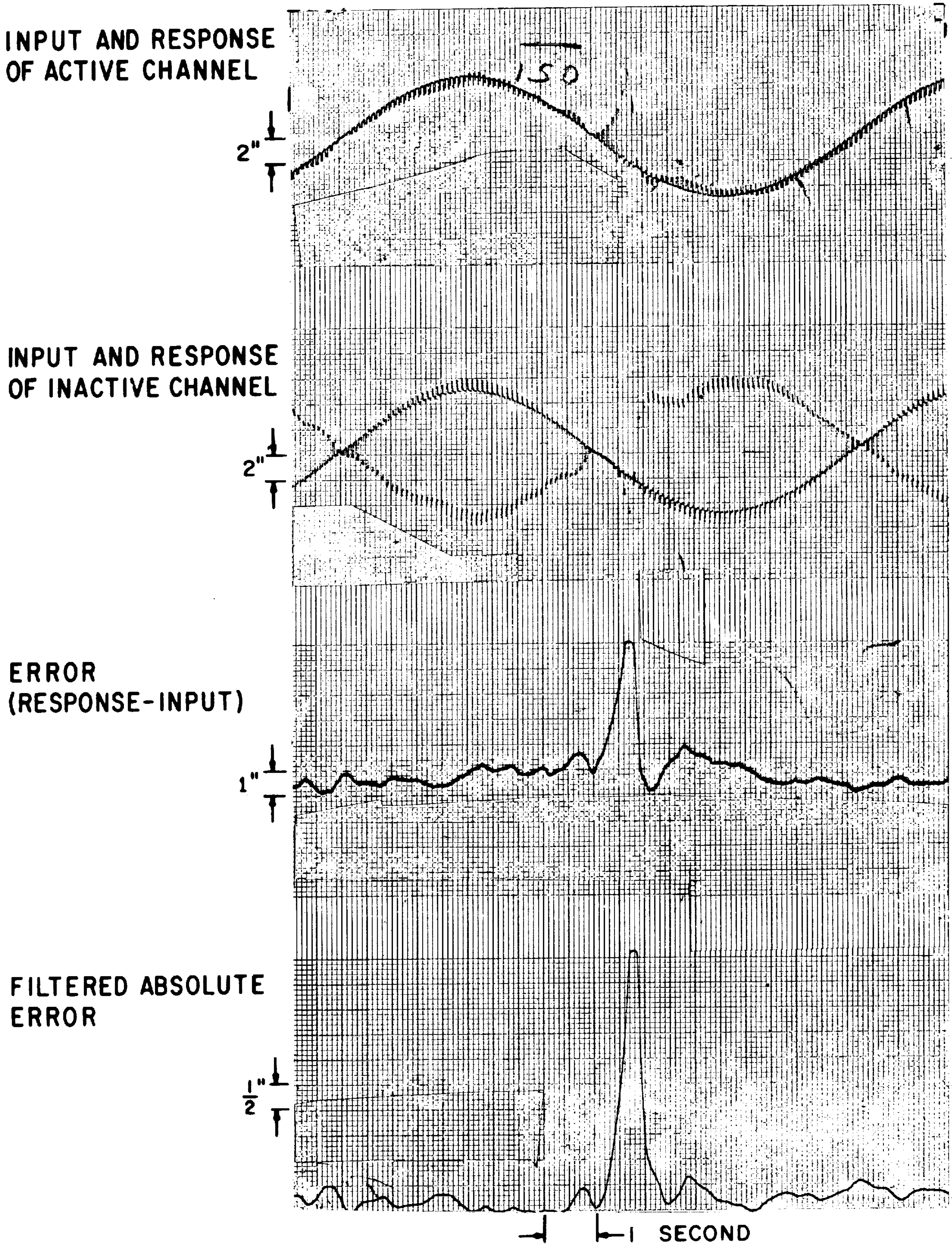

FIG. 2 POLARITY REVERSAL TRANSITION (+2:−2)

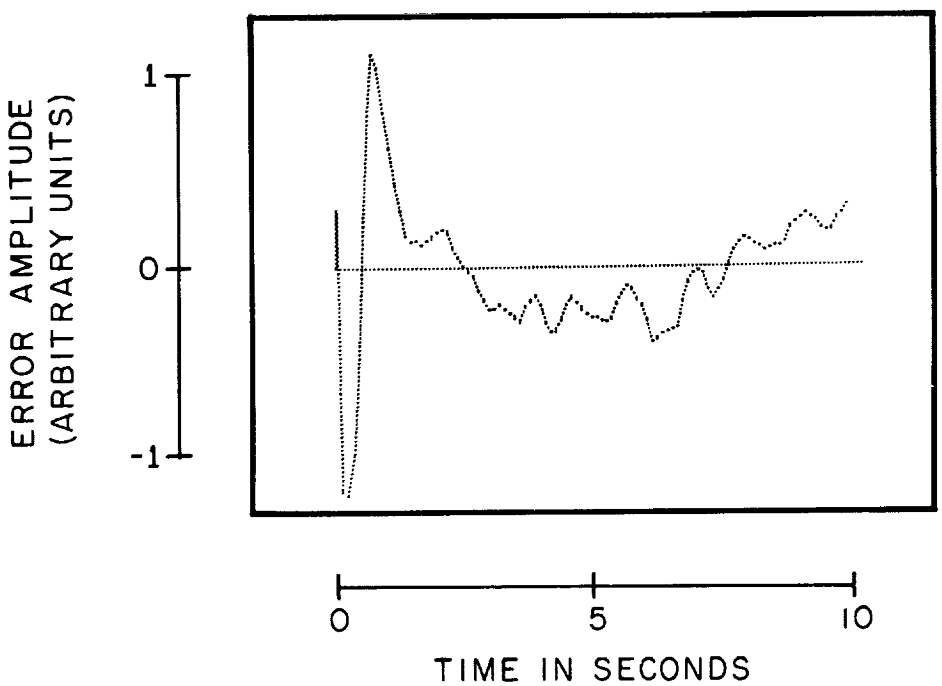

FIG. 3 AVERAGE ERROR FOLLOWING GAIN INCREASE (+1:+4)

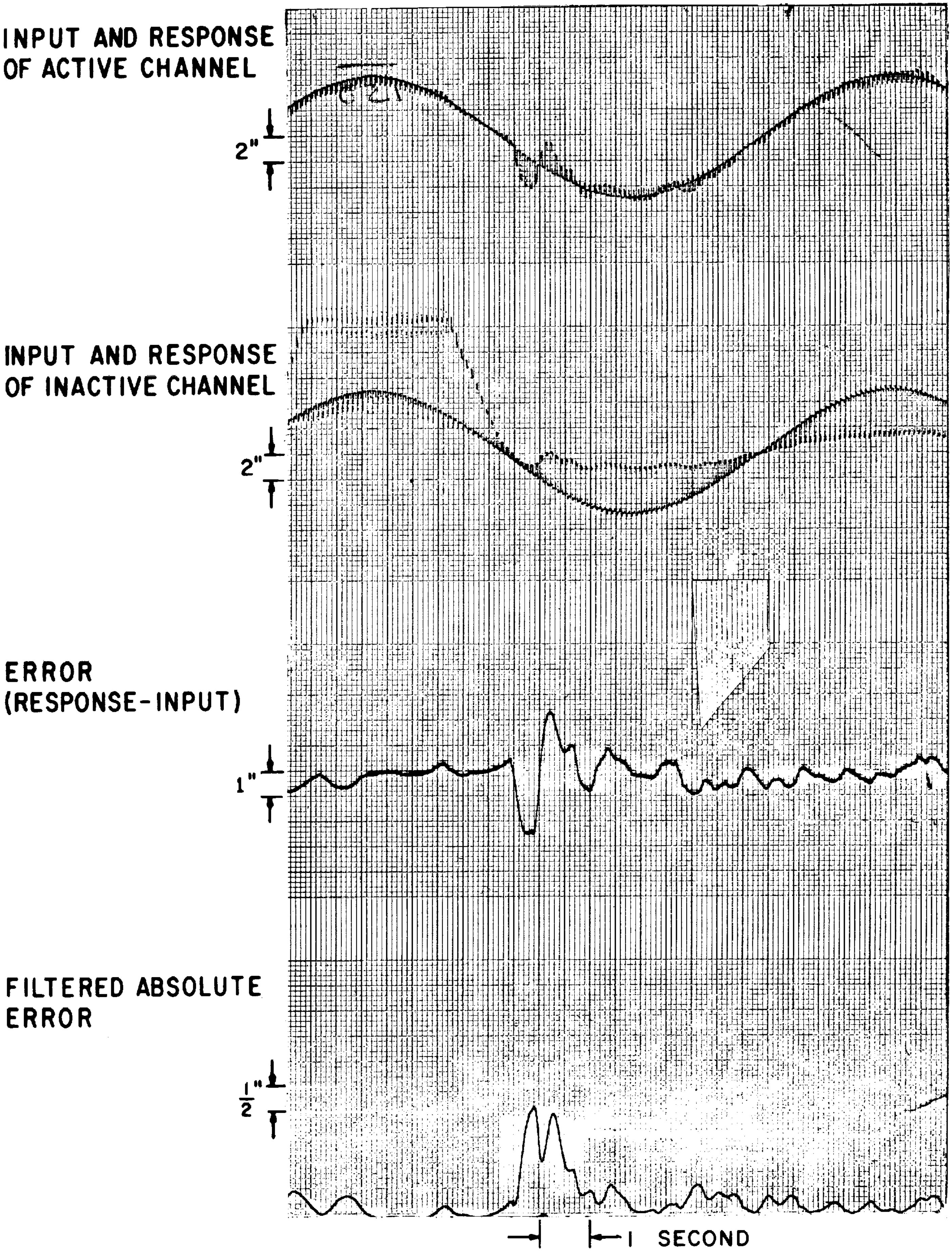

FIG. 4 GAIN INCREASE (+1:+4)

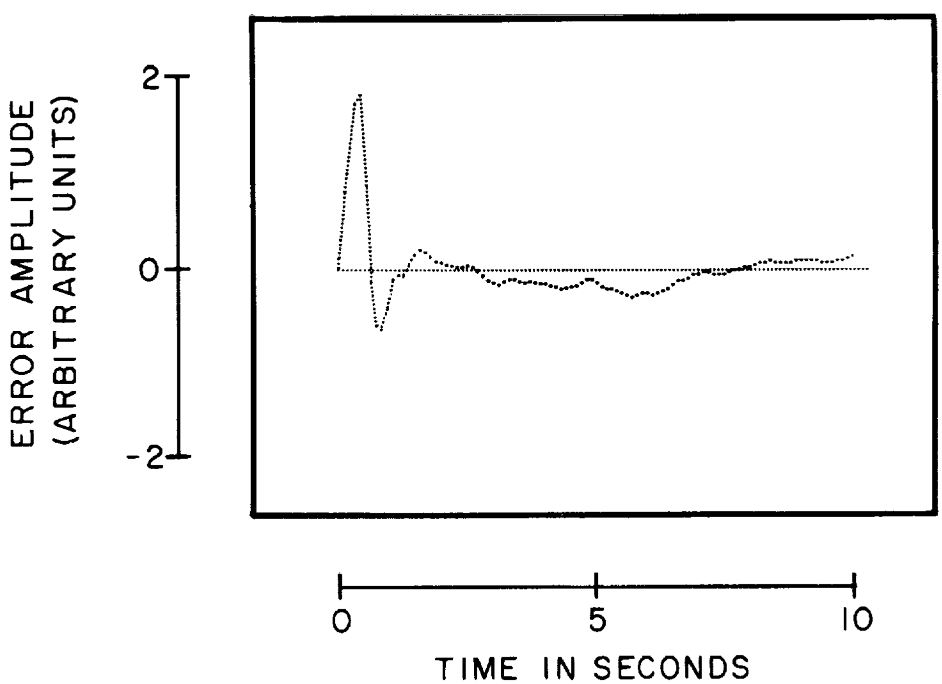

FIG. 5 AVERAGE ERROR FOLLOWING POLARITY REVERSAL AND GAIN INCREASE (+1:−4)

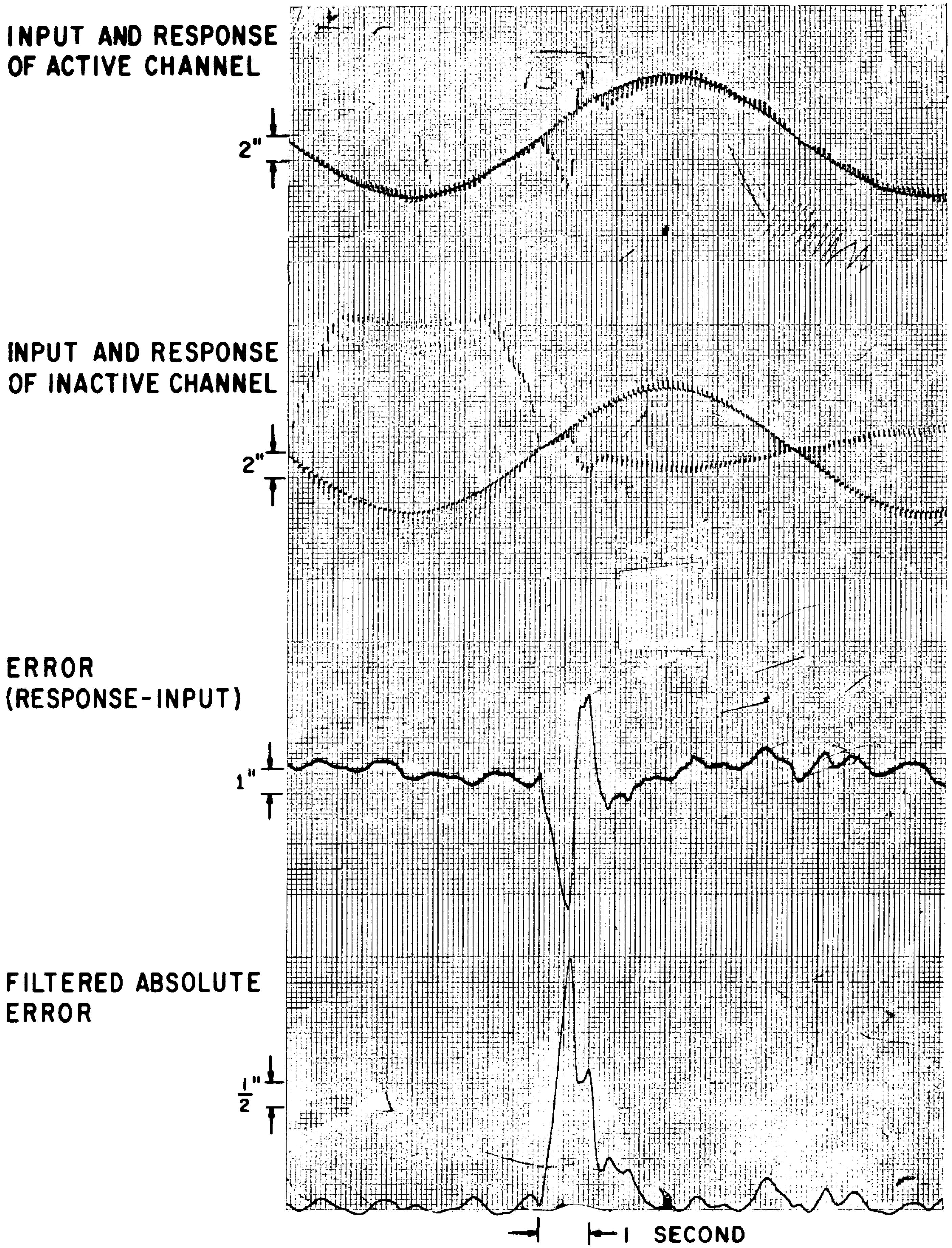

FIG. 6 POLARITY REVERSAL AND GAIN INCREASE (+1:-4)

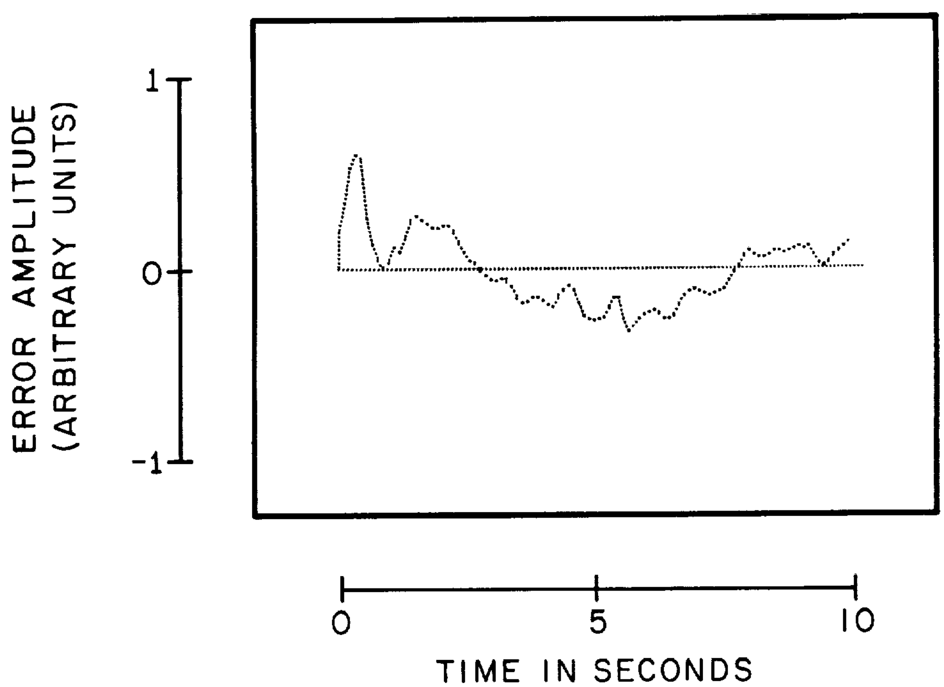

FIG. 7 AVERAGE ERROR FOLLOWING GAIN DECREASE (+4:+1)

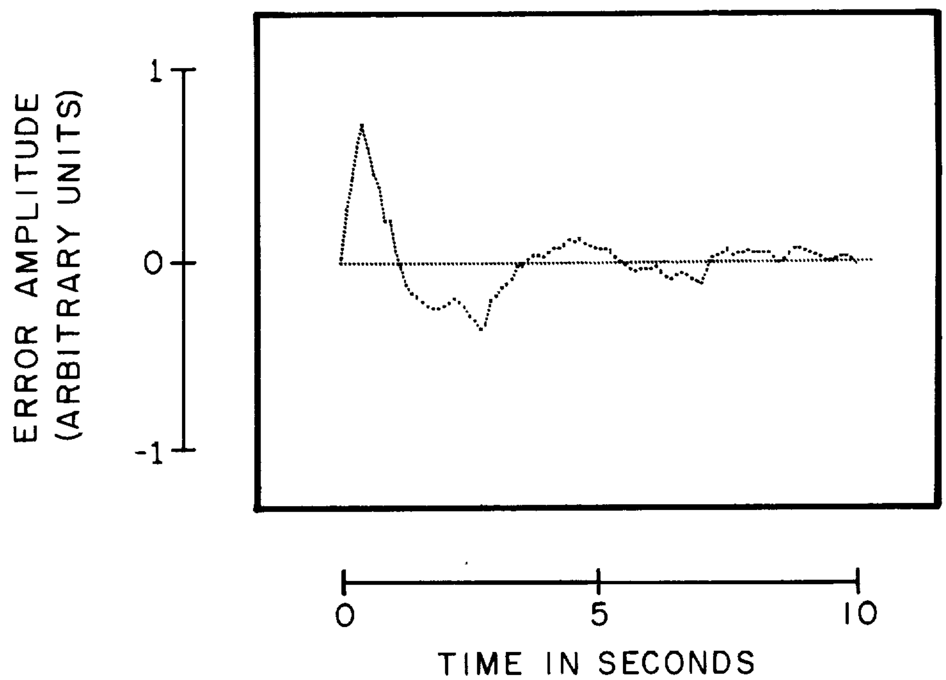

FIG. 8 AVERAGE ERROR FOLLOWING POLARITY REVERSAL (+2:-2); RANDOM INPUT

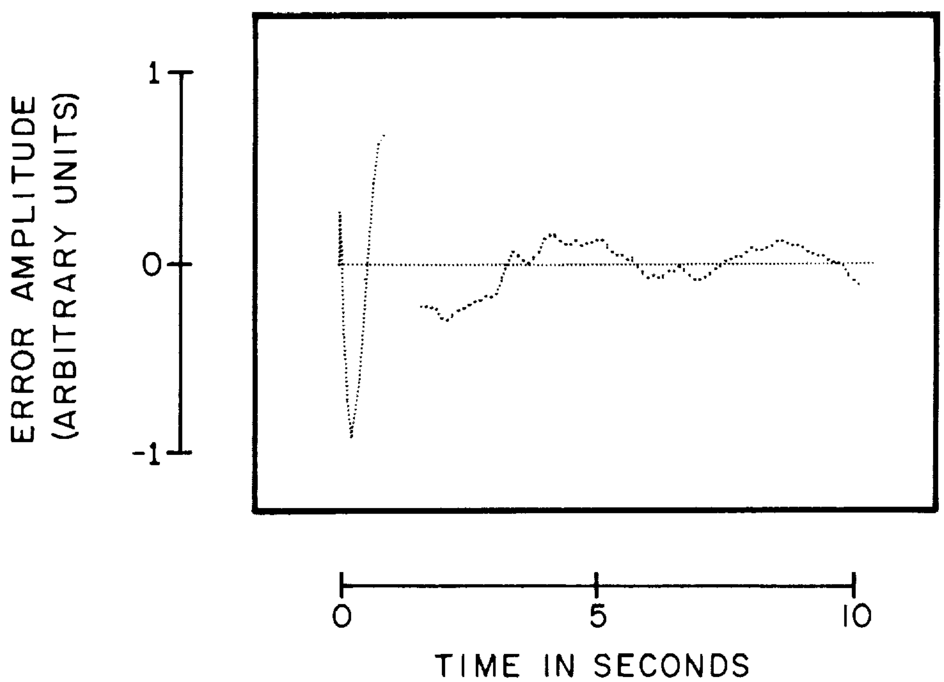

FIG. 9 AVERAGE ERROR FOLLOWING GAIN INCREASE (+1:+4); RANDOM INPUT